HL Tau: 3-D Polarisation Modelling and Magnetic Field Structure

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Abstract.   We describe 3-dimensional Monte Carlo modelling of HL Tau in the near infrared with aligned non-spherical grains. JHK linear polarimetry with 0.4-0.6 arcsec resolution from Subaru and UKIRT is fitted in detail, providing information about the structure of the system, the grain properties and perhaps also the magnetic field. Circular polarisation models are also presented, showing how near infrared circular polarimetry will provide the key to measuring magnetic field structure in protostars on the scale of the solar system, provided that circular polarimeters become available. This is illustrated with recently obtained circular polarimetry of the intermediate mass YSO HH135.

1.   Introduction

HL Tau is among the most well studied of all Young Stellar Objects (YSOs). It is a low mass YSO in the nearby Taurus-Auriga star formation region with a spectral energy distribution which is Class I but relatively flat between wavelengths 2 to 60 μm (Men'shchikov, Henning & Fischer 1999). It retains a large circumstellar envelope, a relic of the formation process, but the its optical depth is low enough that the central regions can be observed in the near infrared waveband with high spatial resolution and signal to noise. HL Tau has been observed with adaptive optics (AO) by Close et al. (1997) which successfully resolved the central protostar in the H and K bands, and marginally detected it at J band. In this paper we show how imaging polarimetry at high spatial resolution (but without AO) reveals further details of the envelope structure, while also providing clues the nature of the dust grains responsible for light scattering in the near infrared. In particular we illustrate the potential of circular polarimetry combined with Monte Carlo modelling to determine the magnetic field structure in YSO envelopes. Full details of the HL Tau data are published in (Lucas et al. 2004). Here we summarise the findings of that paper and use circular polarimetry of HH135, a more distant YSO, to further illustrate the potential of this method.

2.   Observations

Near infrared imaging polarimetry was independently carried out with Subaru and UKIRT on 17th January 2001 and 28th December 2000 respectively. UKIRT observations were made in the J, H and K bands with the camera IRCAM, and the dual beam IRPOL-2 polarimeter. Subaru data were taken with the Coronographic Imager with Adaptive Optics (CIAO) during the commissioning of that instrument, not using AO. The Subaru observations were conducted in H and K bands, and polarimetry used a modulator and a wire grid (single beam). The UKIRT Service dataset suffered from an offset from correct focus which slightly reduced the spatial resolution and data quality. However the spatial resolution was still 0.4 to 0.6 arcsec and the focus tracking system provided excellent image stability, which was verified by the consistency of subsets of the polarisation measurements in small apertures and the good agreement between the Subaru and UKIRT datasets.
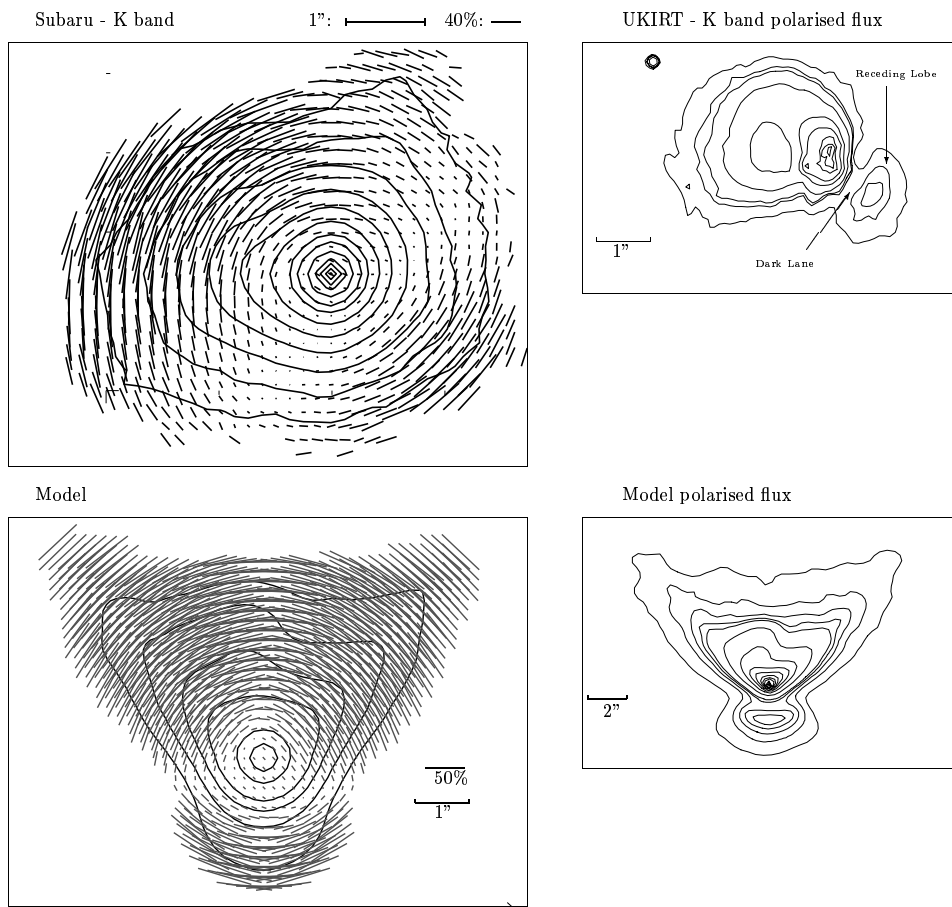

Figure 1.   (upper panels) K band data (north is up and east is to the left). (lower panels) model results, with the disc axis oriented vertically.

3.   Results

The data in Figure 1 show that the nebula has the centrosymmetric pattern expected for scattered light, with the focus near the central point source. Following Close et al. we interpret the point source as the protostar itself with a possible small contribution from hot dust in its immediate environs. By contrast the J band data (not shown) showed a spatially extended peak indicating that the protostar was obscured when observed at 1.25 μm in 0.5 arcsec seeing.

The model assumes that the protostar is surrounded by a small, physically thin accretion disc (radius 150 AU) and a larger scale envelope (1300 AU radius) with a partially evacuated bipolar cavity. It was necessary to include knots of dust within the cavity to reproduce the structure seen in polarised flux: the well defined receding lobe and the diffuse knot seen in the approaching lobe. A 3-D model was required to reproduce the off axis knot in the approaching lobe. A forced scattering procedure was employed to do this efficiently, following the method described by Wood & Reynolds (1999). The inner accretion disc observed at millimetre wavelengths (eg. Wilner et al. (1996)) is not detected here and has little effect on the model results. For the envelope, a density function with a radius-independent $r^{-1.5}$ power law, and a parameterised vertical density gradient was used to produce successful model fits shown in Figure 1. The best fit model has a modest but definitely non zero vertical density gradient. Curved, approximately parabolic cavity walls were found to better reproduce the data than a conical cavity.

The Monte Carlo model fit yield the following additional results. (1) The optical depth to the protostar was fitted at each wavelength and this led us to derive a somewhat shallower near infrared extinction law than that measured for interstellar dust: the J to K opacity ratio $\kappa(J/K) = 2.1 \pm 0.3$, compared with values ranging from 2.48 to 2.89 which are quoted for the interstellar medium. (2) The system inclination is between $66°$ and $71°$, which is toward the upper end of the range determined from millimetre waveband observations of the elongation of the inner accretion disc. (3) The albedo, ω, of the dust grains is $\omega_H \geq 0.4$, $\omega_K \geq 0.2$ in the K and H bands respectively.

The shallow extinction law and the reasonably high albedo both indicate the presence of some large grains in the dust mixture. Evidence for small grains comes from the high polarisation seen in the outer parts of the nebula: up to 80% at K band and 75% at J band. Mie scattering calculations indicate that these constraints require a grain mixture with a small real component of refractive index and significant absorptivity. An example grain mixture with these properties is composed of small (0.07 μm) silicate cores with thick mantles of dirty water ice such that the total grain radius extends up to 1.2 μm, with an $r^{-3.5}$ size distribution. Such a model is qualitatively supported by observations of strong water ice absorption in the 3 μm spectrum of HL Tau. However a model with porous grains might also have the required small refractive index (suggested by Ludmilla Kolokolova at the conference) and therefore should also be investigated.

The most interesting feature of the polarisation maps is that the polarisation vectors associated with the protostar are inclined by $\sim 40°$ to the disc axis. The position angle and degree of polarisation observed by UKIRT and Subaru around the protostar are a little different (see Table 1) but the structure is qualitatively

the same in both datasets. If we adopt P.A.=35° as the orientation of the disc axis (the value for the mm disc observed by Mundy et al. (1996); Wilner et al. (1996)) then the data in Table 1 indicate that the polarisation vectors associated with the point source are inclined by $\sim 40°$ to the disc axis.

Table 1 - Polarisation of the central point source

Data	P.A.	Polarisation
UKIRT K band	79°.7	$3.3\% \pm 0.3\%$
UKIRT H band	77°.4	$3.7\% \pm 0.3\%$
Subaru K band	68.5°	$6.8\% \pm 1.7\%$

Note: results are for a 0.4 arcsec diameter aperture centred on the protostar.

The polarisation of the point source is interpreted as the result of dichroic extinction of light from the protostar by aligned non-spherical grains. This interpretation is supported by the observation of a distortion of the centrosymmetric pattern between at distances from 0.5 to 1.5 arcsec from the point source, which is consistent with a dichroic extinction pattern that is superimposed upon the centrosymmetric pattern produced by scattering.
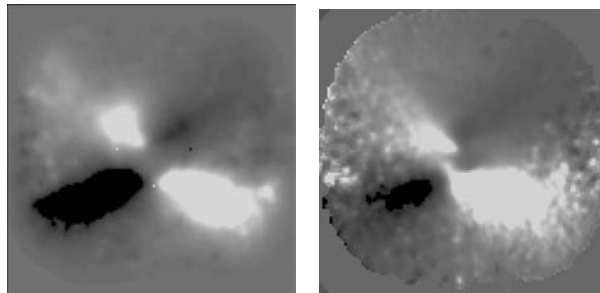

Figure 2.   Circular polarisation models. V/I ranges from 2% RCP (dark) to 2% LCP (bright) for this model with 1.02:1 oblate grain axis ratio. (left) axial magnetic field model. (right) pinched and twisted field model.

However, assuming the dichroic extinction interpretation is correct, this provides information only for a single line of sight. In this case the field could be pinched and twisted (as in the model in Figure 1) or simply globally misaligned with the disc axis. It is here that circular polarimetry becomes useful. The model in Figure 1 incorporates mildly oblate spheroids which are perfectly aligned with a pinched and twisted magnetic field (for details of the algorithm see Lucas (2003); Lucas et al. (2004). The oblate spheroids produce the linear polarisation toward the protostar by dichroic extinction and they also produce significant circular polarisation in the outer parts of the nebula. Figure 2 illustrates the different circular polarisation patterns produced by different model field structures in the HL Tau envelope. Aligned non-spherical particles can produce circular polarisation by scattering or by extinction (birefringence). In this
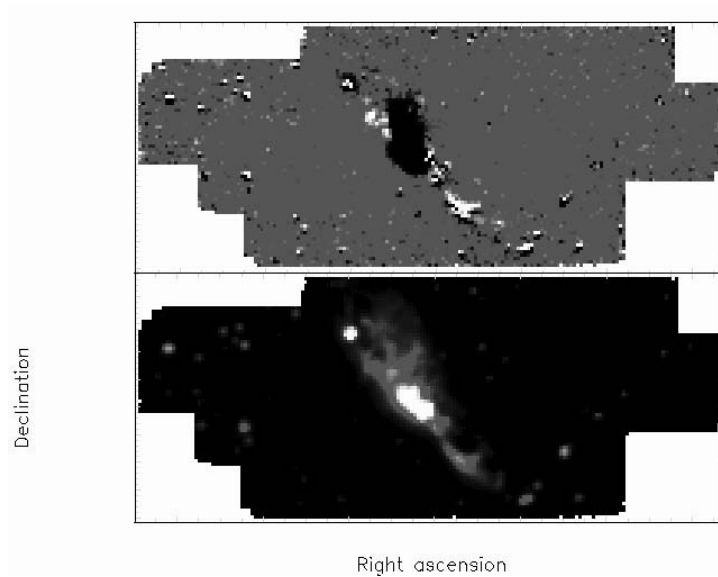
Figure 3.   HH135. (lower panel) image (Stokes I). (upper-panel) Stokes V.

case the circular polarisation of the model arises from scattering, since the optical depth in the outer parts of the envelope is low. Observations by Takami et al. (1999) place an upper limit of CP< 2% in the brighter parts of the nebula but the models indicate that the polarisation is highest in the faint, receding part of the nebula. Hence, deep imaging with circular polarimeters on large telescopes may be needed to measure magnetic field structures in YSO envelopes.

4.   Circular Polarimetry of HH135

HH135 is an intermediate mass YSO at a distance of $\approx$1 kpc, with system axis inclined by $\sim 80°$ to the line of sight. Figure 3 shows a K band image and circular polarisation map. The circular polarisation seen here is up to 8% at K band, and the structure is somewhat similar to that of the pinched and twisted field model for HL Tau. Most of the polarisation is in negative Stokes V, but at the edges of the bipolar cavity negative V is seen. The model for this source is still under construction, and is complicated by the fact that linear polarimetry shows much lower polarisation ($\sim$ 2%) along the system axis than at adjacent points a few arcsec to either side ($\sim$ 40%.)

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